

# Remaining inconsistencies with solar neutrinos: can spin flavour precession provide a clue?

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**Abstract.** A few inconsistencies remain after it has been ascertained that LMA is the dominant solution to the solar neutrino problem: why is the SuperKamiokande spectrum flat and why is the Chlorine rate prediction over two standard deviations above the data. There also remains the unanswered and important question of whether the active neutrino flux is constant or time varying. We propose a scenario involving spin flavour precession to sterile neutrinos with three active flavours that predicts a flat SuperK spectrum and a Chlorine rate prediction more consistent with data. We also argue that running the Borexino experiment during the next few years may provide a very important clue as to the possible variability of the solar neutrino flux.

Ever since the first KamLAND results were released [1], the large mixing angle solution (LMA) [2] has been generally accepted to be the dominant one for the solar neutrino problem. Nevertheless a few intriguing questions remain open in this area. In fact it is customary to assume that the active solar neutrino flux is constant, although the possibility of its time variation is still a challenging issue to be investigated [3], [4] both experimentally and theoretically. Moreover, the observed flatness of the SuperKamiokande spectrum [5] and the Chlorine rate prediction lying at more than  $2\sigma$  above the data [6] are disturbing facts providing evidence that LMA may not be the ultimate solution.

Based on these motivations, we developed a model which includes a light sterile neutrino in addition to the three active ones [7] which communicates with these by means of transition magnetic moments. Somewhere inside the sun, in a location determined by the balance between the solar density and the mass square difference between the sterile neutrino and the active ones, a resonant transition may occur converting the latter into the sterile in the presence of a large magnetic field. Hence, besides the solar and atmospheric mass differences, a third one is introduced implying another resonance in addition to the LMA one. For simplicity no extra vacuum mixing angle is assumed, so that the matter Hamiltonian which includes vacuum propagation is [7]

$$H_M = \begin{pmatrix} \frac{\Delta m_{01}^2}{2E} & \tilde{\mu}_1 B & \tilde{\mu}_2 B & \tilde{\mu}_3 B \\ \tilde{\mu}_1 B & V_n + V_c u_{e1}^2 & V_c u_{e1} u_{e2} & V_c u_{e1} u_{e3} \\ \tilde{\mu}_2 B & V_c u_{e1} u_{e2} & \frac{\Delta m_{21}^2}{2E} + V_n + V_c u_{e2}^2 & V_c u_{e2} u_{e3} \\ \tilde{\mu}_3 B & V_c u_{e1} u_{e3} & V_c u_{e2} u_{e3} & \frac{\Delta m_{31}^2}{2E} + V_n + V_c u_{e3}^2 \end{pmatrix}. \quad (1)$$

Here  $V_c$ ,  $V_n$  are the charged and neutral current interaction potentials,  $\tilde{\mu}_{1,2,3}$  are transition magnetic moments between mass eigenstates 0 and 1, 2, 3 and  $u_{e_i}$  are the first row entries of the (3x3) PMNS matrix. The newly introduced mass squared difference  $\Delta m_{01}^2$  is smaller than  $\Delta m_{21}^2$  and so the spin flavour precession resonance lies closer to the solar surface than the LMA one.

We have used the numerical integration of the Hamiltonian equation and considered the following two field profiles which are approximately complementary to each other [7]

*Profile 1*

$$B_1 = B_0 / \cosh[6(x - 0.71)] \quad (0 < x < 0.71), \quad B_1 = B_0 / \cosh[15(x - 0.71)] \quad (0.71 < x < 1)$$

*Profile 2*

$$B_2 = B_0 / [1 + \exp[10(2x - 1)]] \quad 0 < x < 1.$$

The experimental data on all rates (Cl, Ga, SK rate and spectrum, SNO rates and spectrum, Borexino [8]) were used to assess the quality of the fits with the following  $\chi^2$  standard definition

$$\chi^2 = \sum_{j_1, j_2} (R_{j_1}^{th} - R_{j_1}^{exp}) \left[ \sigma^2(tot) \right]_{j_1 j_2}^{-1} (R_{j_2}^{th} - R_{j_2}^{exp}).$$

Using the experimental values of  $\Delta m_{21}^2$ ,  $\Delta m_{atm}^2$ ,  $\theta_{12}$ ,  $\theta_{atm}$  and  $B_0$  (field at the peak),  $\Delta m_{01}^2$  as free parameters, we obtained the fits for profile 1 shown in table I.

$B_0(kG)$	$\sin \theta_{13}$	Ga	Cl	SK	SNO <sub>NC</sub>	SNO <sub>CC</sub>	SNO <sub>ES</sub>	$\chi_{rates}^2$	$\chi_{SK_{sp}}^2$	$\chi_{SNO}^2$	$\chi_{gl}^2$
0	0	67.2	2.99	2.51	5.62	1.90	2.49	0.07	42.7	57.2	99.9
	0.1	66.0	2.94	2.49	5.62	1.87	2.46	0.30	42.1	55.2	97.6
	0.13	65.0	2.90	2.46	5.62	1.84	2.44	0.62	41.7	53.7	96.0
140	0	66.4	2.82	2.32	5.37	1.76	2.31	0.20	37.6	46.0	83.8
	0.1	65.3	2.77	2.29	5.37	1.73	2.28	0.53	37.9	44.9	83.3
	0.13	64.3	2.72	2.27	5.37	1.70	2.25	0.95	38.4	44.1	83.4

Table I.  $\chi^2$ 's and rates (in SNU for Cl and Ga experiments, in  $10^6 cm^{-2} s^{-1}$  for SK and SNO).

For the best fit we found  $B_0=140$  kG,  $\Delta m_{01}^2 = 1.25 \times 10^{-7} eV^2$  with transition moments between flavour eigenstates  $\mu_{(\mu, \tau)s} = 1.4 \times 10^{-12} \mu_B$  and  $\mu_{es} \leq \mu_{(\mu, \tau)s}$ .

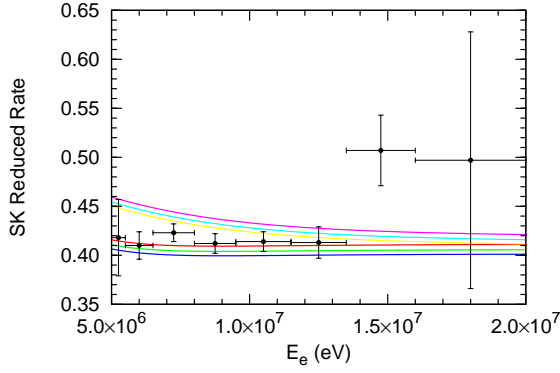
The corresponding results for the SuperKamiokande and Borexino spectra in the case of profile 1 are shown in figs. 1 and 2. For profile 2 the quality of the fits and the results are much the same, except that the best fit is obtained for  $B_0 = 0.75 MG$ ,  $\Delta m_{01}^2 = 2.7 \times 10^{-6} eV^2$ .

From table I and figs. 1, 2 a clear preference of the data for a sizable magnetic field is apparent. In fact

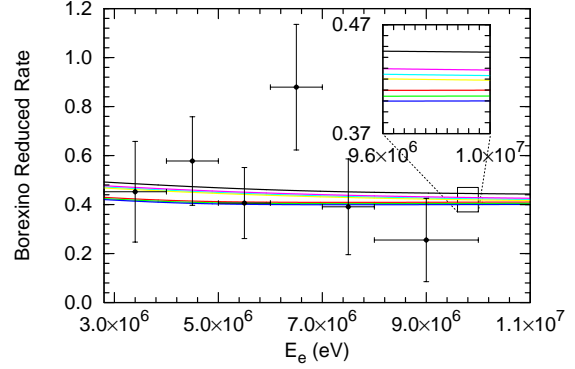
- the SuperKamiokande spectrum becomes flat
- the rate prediction for the Chlorine experiment strongly improves (instead of a  $2\sigma$  discrepancy, a prediction within  $1\sigma$  of the data is obtained).

Furthermore no conclusion can be drawn on the value of  $\theta_{13}$ . As for the Ga rate, vanishing and sizable fields are equivalent, as both classes of predictions lie within  $1\sigma$  of the central value. Regarding Borexino it is unclear whether it can favour either a negligible or a sizable solar magnetic field owing to the size of the experimental errors. Likewise no conclusion is obtained regarding the magnitude of  $\theta_{13}$  in this case. So as this stage Borexino results are consistent with both a vanishing and a large field.

Since the intensity of the solar magnetic field is possibly related to the solar activity, the time dependence of the data is an open possibility consistent with this model. So we examine the periods in which the data were taken. We see that



**Figure 1.** SuperKamiokande spectrum: data points and predictions for vanishing field (upper curves) and  $B_0 = 140kG$  (lower curves). From top to bottom and for each set  $\sin\theta_{13} = 0, 0.1, 0.13$ .



**Figure 2.** The same as fig.1 for Borexino spectrum and  $^8B$  neutrinos: all experimental errors are larger here and no conclusion can be drawn as for the preference of the data.

- the SuperKamiokande spectrum refers to the period from May 31, 1996 to July 15, 2001 during which the average sunspot number was 65
- the Borexino  $^8B$  spectrum refers to the period July 15, 2007 to June 21, 2008 when the average sunspot number was 4
- in most of the former period the solar magnetic activity increased and reached an 11 year peak in the Summer of 2000, whereas in the latter the activity was continuously at its minimum.

Therefore in the light of this model one expects the Borexino  $^8B$  spectrum to coincide with the LMA prediction and the SuperKamiokande one to reflect a moderately active sun. If and when Borexino are able to reduce their errors to 1/3 (2/3 reduction), solar activity will probably have increased. Depending on whether this will be reflected in the increase of the solar field strength and a consequent decrease in the event rate, an opportunity may arise to clearly test the model.

Signatures of profiles 1 and 2 may also be distinguishable. In fact for profile 1 and Borexino phase 1 (low energy fluxes,  $E < 1.7MeV$ ) all  $\nu$ 's have their resonances at  $x < 0.5$ . Here the field is weak and the density is large so that the event rate modulation will be too small ( $\simeq 1\%$ ) to ever be seen. For profile 2 and Borexino phase 1, resonances lie at  $x < 0.23$  where the field is close to maximal ( $O(1MG)$ ), so that a field modulation in connection with solar activity accounts for as much as ( $\simeq 9\%$ ) variability in the Borexino event rate. Hence low energy fluxes can detect modulation for profile 2 but not for profile 1. Finally the  $^8B$  flux (seen by SK and Borexino) can detect modulation for both classes of profiles, so it cannot tell profile 1 from 2.

Hence we believe it essential to keep Borexino taking data for all neutrino fluxes during at least the first half of the present solar cycle expected to peak in 2011 or 2012 and present their data in time bins.

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